Moisture Tables--C.F.Marvin.
W. B. No.171, 1898.

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U. S. DEPARTMENT OF AGRICULTURE,

WEATHER BUREAU.

MOISTURE TABLES.

Prepared under direction of WILLIS L. MOORE, Chief of Weather Bureau.

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MOISTURE TABLES.[1]

The quantity of moisture mixed with the air under different conditions as to temperature and degree of saturation often plays an important part in the operation of blast furnaces, drying kilns, cotton mills, steel mills, etc. The metallurgist, especially, is awakening to the importance of taking full account of the moisture in the air that incidentally, or designedly, is often a part of extensive chemical operations involved in the production of steel and iron.

From time to time letters requesting information on these questions have been received by the Chief of the Weather Bureau, and it has seemed advisable to publish a general answer to such inquiries in the shape of the following notes and table.

The weight of a unit volume of vapor is given in the revised editions of meteorological tables only for conditions of complete saturation, whereas, in ordinary practice we deal nearly always with cases of partial saturation, and it is believed the table below will be useful to many and obviate the necessity of special computations.

Faulty conceptions.—A false notion that the air has a certain capacity for moisture is widely prevalent, and is perpetuated by all such expressions as "The air is partly saturated with moisture," "Weight of aqueous vapor in a cubic foot of *saturated air*," etc.

It should always be clearly observed that the presence of the moisture in any given space is independent of the presence or absence of air in the same space except that the air retards the diffusion of the vapor particles. It is more correct to say, in the above cases, that the *space* is partly saturated with moisture, or the moisture is partly saturated or is superheated. By all means use the phrase "Weight of a cubic foot of saturated aqueous vapor," not "Weight of aqueous vapor in a cubic foot of saturated air."

The amount of saturated aqueous vapor that can exist in any given space depends entirely upon the temperature. It appears that the vapor may be supersaturated under certain peculiar conditions, but this is a special and an unstable state which need not be considered in the present connection. When the vapor is saturated, it will exert a certain pressure which varies with the temperature and which so-called "maximum pressure" has been measured with greater or less precision over a long range of temperature from about 60° below zero F., to far above the boiling point of water.

Saturated aqueous vapor is but little more than half as heavy as the same volume of dry air under like conditions of temperature and pressure. In all ordinary computations

[1] Reprinted from the Monthly Weather Review; May, 1898.

it is assumed that the expansion and contraction of partially saturated aqueous vapor is in accordance with the same laws as apply to air and ordinary gases, which do not easily condense to the liquid state.

The adopted density of saturated aqueous vapor is not determined directly from experiment, but is deduced theoretically from the observed fact that two volumes of hydrogen and one of oxygen combine to produce two volumes of water vapor.

The weights of unit volumes of hydrogen, oxygen, and dry air are accurately known, from which the specific gravity of aqueous vapor is found to be 0.6221.

The weight of a cubic meter of saturated aqueous vapor is given by the equation:

$$W = 0.6221 \frac{A}{1 + kt} \frac{F}{760},$$

in which t is the temperature, centigrade, and F the corresponding pressure, in millimeters, at saturation. A is the weight of a cubic meter of air, under standard conditions = 1.29278 kilogram, k is the coefficient of expansion of air = 0.003667.

If English units of temperature, pressure, and weight are used, we find the weight of a cubic foot of saturated aqueous vapor in grains is:

$$W = 11.7459 \frac{F'}{1 + 0.002037\ (t - 32)}.$$

This formula gives the weights found in the column headed "100" in the accompanying table. Above 32° the values of F' employed were those deduced from Regnault's observations, by Broch, for the International Bureau of Weights and Measures. Broch's reduction is unsatisfactory for temperatures below 32°, and this portion of the table is based upon saturation pressures experimentally observed by the writer and described in Appendix 10, Annual Report of the Chief Signal Officer, 1891.

When the water vapor present in any given space is not saturated, this fact is generally expressed by the degree of humidity assigned to it. For example, we say the relative humidity, that is the percentage of saturation, is 60. This means that only 60 per cent of the vapor that might at the prevailing temperature exist in the space under consideration is present; hence, 40 per cent more vapor must be added in order that the space may be saturated. We may deduce the percentages of saturation either as a ratio of the weights, or as a ratio of pressures, with identical results, because in all such computations it is assumed without important errors that partially saturated vapor expands and compresses strictly proportional to the temperature and pressure. From this it follows that the weight of vapor at a given percentage of saturation is found by multiplying the weight corresponding to saturation by the relative humidity.

Weight of a cubic foot of aqueous vapor at different temperatures and percentages of saturation.

Temperature, ° F.	Percentage of saturation.									
	10	20	30	40	50	60	70	80	90	100
	Grains.									
—20	0.017	0.033	0.050	0.066	0.083	0.100	0.116	0.133	0.149	0.166
19	0.017	0.035	0.052	0.070	0.087	0.104	0.122	0.139	0.157	0.174
18	0.018	0.037	0.055	0.074	0.092	0.110	0.129	0.147	0.166	0.184
17	0.020	0.039	0.059	0.078	0.098	0.118	0.137	0.157	0.176	0.196
16	0.021	0.041	0.062	0.083	0.104	0.124	0.145	0.166	0.186	0.207
—15	0.022	0.044	0.065	0.087	0.109	0.131	0.153	0.174	0.196	0.218
14	0.023	0.046	0.069	0.092	0.116	0.139	0.162	0.185	0.208	0.231
13	0.024	0.049	0.073	0.097	0.122	0.146	0.170	0.194	0.219	0.243
12	0.026	0.051	0.077	0.103	0.128	0.154	0.180	0.206	0.231	0.257
11	0.027	0.054	0.081	0.108	0.135	0.162	0.189	0.216	0.243	0.270
—10	0.028	0.057	0.086	0.114	0.142	0.171	0.200	0.228	0.256	0.285
9	0.030	0.060	0.090	0.120	0.150	0.180	0.210	0.240	0.270	0.300
8	0.032	0.063	0.095	0.126	0.158	0.190	0.221	0.253	0.284	0.316
7	0.033	0.066	0.100	0.133	0.166	0.199	0.232	0.266	0.299	0.332
6	0.035	0.070	0.105	0.140	0.175	0.210	0.245	0.280	0.315	0.350
— 5	0.037	0.074	0.111	0.148	0.185	0.222	0.259	0.296	0.333	0.370
4	0.039	0.078	0.117	0.156	0.194	0.233	0.272	0.311	0.350	0.389
3	0.041	0.082	0.123	0.164	0.206	0.247	0.288	0.329	0.370	0.411
2	0.043	0.087	0.130	0.174	0.217	0.260	0.304	0.347	0.391	0.434
— 1	0.046	0.091	0.137	0.183	0.228	0.274	0.320	0.366	0.411	0.457
0	0.048	0.096	0.144	0.192	0.240	0.289	0.337	0.385	0.433	0.481
+ 1	0.050	0.101	0.152	0.202	0.252	0.303	0.354	0.404	0.454	0.505
2	0.053	0.106	0.159	0.212	0.264	0.317	0.370	0.423	0.476	0.529
3	0.055	0.111	0.166	0.222	0.277	0.332	0.388	0.443	0.499	0.554
4	0.058	0.116	0.175	0.233	0.291	0.349	0.407	0.466	0.524	0.582
5	0.061	0.122	0.183	0.244	0.305	0.366	0.427	0.488	0.549	0.610
6	0.064	0.128	0.192	0.256	0.320	0.383	0.447	0.511	0.575	0.639
7	0.067	0.134	0.201	0.268	0.336	0.403	0.470	0.537	0.604	0.671
8	0.070	0.141	0.211	0.282	0.352	0.422	0.493	0.563	0.634	0.704
9	0.074	0.148	0.222	0.296	0.370	0.443	0.517	0.591	0.665	0.739
10	0.078	0.155	0.233	0.310	0.388	0.466	0.543	0.621	0.698	0.776
11	0.082	0.163	0.245	0.326	0.408	0.490	0.571	0.653	0.734	0.816
12	0.086	0.171	0.257	0.342	0.428	0.514	0.599	0.685	0.770	0.856
13	0.090	0.180	0.269	0.359	0.449	0.539	0.629	0.718	0.808	0.898
14	0.094	0.188	0.282	0.376	0.470	0.565	0.659	0.753	0.847	0.941
15	0.099	0.197	0.296	0.394	0.493	0.592	0.690	0.789	0.887	0.986
16	0.103	0.206	0.310	0.413	0.516	0.619	0.722	0.826	0.929	1.032
17	0.108	0.216	0.324	0.432	0.540	0.648	0.756	0.864	0.972	1.080
18	0.113	0.226	0.338	0.451	0.564	0.677	0.790	0.902	1.015	1.128
19	0.118	0.236	0.354	0.472	0.590	0.709	0.827	0.945	1.063	1.181
20	0.124	0.247	0.370	0.494	0.618	0.741	0.864	0.988	1.112	1.235
21	0.129	0.259	0.388	0.518	0.647	0.776	0.906	1.035	1.165	1.294
22	0.136	0.271	0.406	0.542	0.678	0.813	0.948	1.084	1.220	1.355
23	0.142	0.284	0.425	0.567	0.709	0.851	0.993	1.134	1.276	1.418
24	0.148	0.297	0.445	0.593	0.742	0.890	1.038	1.186	1.335	1.483
25	0.155	0.310	0.465	0.620	0.776	0.931	1.086	1.241	1.396	1.551
26	0.162	0.325	0.487	0.649	0.812	0.974	1.136	1.298	1.461	1.623
27	0.170	0.339	0.509	0.679	0.848	1.018	1.188	1.358	1.527	1.697
28	0.177	0.355	0.532	0.709	0.886	1.064	1.241	1.418	1.596	1.773
29	0.185	0.371	0.556	0.741	0.926	1.112	1.297	1.482	1.668	1.853
30	0.194	0.387	0.580	0.774	0.968	1.161	1.354	1.548	1.742	1.935
31	0.202	0.404	0.607	0.809	1.011	1.213	1.415	1.618	1.820	2.022
32	0.211	0.422	0.634	0.845	1.056	1.268	1.479	1.690	1.902	2.113
33	0.219	0.439	0.658	0.878	1.097	1.316	1.536	1.755	1.975	2.194
34	0.228	0.456	0.684	0.912	1.140	1.367	1.595	1.823	2.051	2.279
35	0.237	0.473	0.710	0.946	1.183	1.420	1.656	1.893	2.129	2.366
36	0.246	0.491	0.737	0.983	1.228	1.474	1.720	1.966	2.211	2.457
37	0.255	0.510	0.765	1.020	1.275	1.530	1.785	2.040	2.295	2.550
38	0.265	0.529	0.794	1.058	1.323	1.588	1.852	2.117	2.381	2.646
+39	0.275	0.549	0.824	1.098	1.373	1.648	1.922	2.197	2.471	2.746

Weight of a cubic foot of aqueous vapor, etc.—Continued.

Temperature. ° F.	Percentage of saturation.									
	10	20	30	40	50	60	70	80	90	100
	Grains.									
+40	0.285	0.570	0.855	1.140	1.424	1.709	1.994	2.279	2.564	2.849
41	0.296	0.591	0.886	1.182	1.478	1.773	2.068	2.364	2.660	2.955
42	0.306	0.613	0.919	1.226	1.532	1.838	2.145	2.451	2.758	3.064
43	0.318	0.635	0.953	1.271	1.588	1.906	2.224	2.542	2.859	3.177
44	0.329	0.659	0.988	1.318	1.647	1.976	2.306	2.635	2.965	3.294
45	0.341	0.683	1.024	1.366	1.707	2.048	2.390	2.731	3.073	3.414
46	0.354	0.708	1.062	1.416	1.770	2.123	2.477	2.831	3.185	3.539
47	0.367	0.733	1.100	1.467	1.834	2.200	2.567	2.934	3.300	3.667
48	0.380	0.760	1.140	1.520	1.900	2.280	2.660	3.040	3.420	3.800
49	0.394	0.787	1.181	1.574	1.968	2.362	2.755	3.149	3.542	3.936
50	0.408	0.815	1.223	1.630	2.038	2.446	2.853	3.261	3.668	4.076
51	0.422	0.844	1.267	1.689	2.111	2.533	2.955	3.378	3.800	4.222
52	0.437	0.874	1.312	1.749	2.186	2.623	3.060	3.498	3.935	4.372
53	0.453	0.905	1.358	1.810	2.263	2.716	3.168	3.621	4.073	4.526
54	0.468	0.937	1.406	1.874	2.342	2.811	3.280	3.748	4.216	4.685
55	0.485	0.970	1.455	1.940	2.424	2.909	3.394	3.879	4.364	4.849
56	0.502	1.003	1.505	2.006	2.508	3.010	3.511	4.013	4.514	5.016
57	0.519	1.038	1.557	2.076	2 596	3.115	3.634	4.153	4.672	5.191
58	0.537	1.074	1.611	2,148	2.685	3.222	3.759	4.296	4.833	5.370
59	0.556	1.111	1.666	2.222	2.778	3.333	3.888	4.444	5.000	5.555
60	0.574	1.149	1.724	2.298	2.872	3.447	4.022	4.596	5.170	5.745
61	0.594	1.188	1.782	2.376	2.970	3.565	4.159	4.753	5.347	5.941
62	0.614	1.228	1.843	2.457	3.071	3.685	4.299	4.914	5.528	6.142
63	0.635	1.270	1.905	2.540	3.174	3.809	4.444	5.079	5.714	6.349
64	0.656	1.313	1.969	2.625	3.282	3.938	4.594	5.250	5.907	6.563
65	0.678	1.356	2.035	2.713	3.391	4.069	4.747	5.426	6.104	6.782
66	0.701	1.402	2.103	2.804	3.504	4.205	4.906	5.607	6.308	7.009
67	0 724	1.448	2.172	2.896	3.620	4.345	5.069	5.793	6.517	7.241
68	0.748	1.496	2.244	2.992	3.740	4.488	5.236	5.984	6.732	7.480
69	0.773	1.545	2.318	3.090	3.863	4.636	5.408	6.181	6.953	7.726
70	0.798	1.596	2.394	3.192	3.990	4.788	5.586	6.384	7.182	7.980
71	0.824	1.648	2.472	3.296	4.120	4.944	5.768	6.592	7.416	8.240
72	0.851	1.702	2.552	3.403	4.254	5.105	5.956	6.806	7.657	8.508
73	0.878	1.756	2.635	3.513	4.391	5.269	6.147	7.026	7.904	8.782
74	0.907	1.813	2.720	3.626	4.533	5.440	6.346	7.253	8.159	9.066
75	0.936	1.871	2.807	3.742	4.678	5.614	6.549	7.485	8.420	9.356
76	0.966	1.931	2.896	3.862	4.828	5.793	6.758	7.724	8.690	9.655
77	0.996	1.992	2.989	3.985	4.981	5.977	6.973	7.970	8.966	9.962
78	1.028	2.055	3.083	4.111	5.138	6.166	7.194	8.222	9.249	10.277
79	1.060	2.120	3.180	4.240	5.300	6.361	7.421	8.481	9.541	10.601
80	1.093	2.187	3.280	4.374	5.467	6.560	7.654	8.747	9.841	10.934
81	1.128	2.255	3.382	4.510	5.638	6.765	7.892	9.020	10.148	11.275
82	1.163	2.325	3.488	4.650	5.813	6.976	8.138	9.301	10.463	11.626
83	1.199	2.397	3.596	4.795	5.994	7.192	8.391	9.590	10.788	11.987
84	1.236	2.471	3.707	4.942	6.178	7.414	8.649	9.885	11.120	12.356
85	1.274	2.547	3.821	5.094	6.368	7.642	8.915	10.189	11.462	12.736
86	1.313	2.625	3.938	5.251	6.564	7.877	9.189	10.502	11.814	13.127
87	1.353	2.705	4.058	5.410	6.763	8.116	9.468	10.821	12.173	13.526
88	1.394	2.787	4.181	5.575	6.968	8.362	9.756	11.150	12.543	13.937
89	1.436	2.872	4.308	5.744	7.180	8.615	10.051	11.487	12.923	14.359
90	1.479	2.958	4.437	5.916	7.395	8.874	10.353	11.832	13.311	14.790
91	1.523	3.047	4.570	6.094	7.617	9.140	10.664	12.187	13.711	15.234
92	1.569	3.138	4.707	6.276	7.844	9.413	10.982	12.551	14.120	15.689
93	1.616	3.231	4.846	6.462	8.078	9.693	11.308	12.924	14.540	16.155
94	1.663	3.327	4.990	6.654	8.317	9.980	11.644	13.307	14.971	16.634
95	1.712	3.425	5.137	6.850	8.562	10.274	11.987	13.699	15.412	17.124
96	1.763	3.525	5.288	7.050	8.813	10.576	12.338	14.101	15.863	17.626
97	1.814	3.628	5.443	7.257	9.071	10.885	12.699	14.514	16.328	18.142
98	1.867	3.734	5.601	7.468	9.336	11.203	13.070	14.937	16.804	18.671
+99	1.921	3.842	5.764	7.685	9.606	11.527	13.448	15.370	17.291	19.212

Weight of a cubic foot of aqueous vapor, etc.—Continued.

Temperature. ° F.	Percentage of saturation.									
	10	20	30	40	50	60	70	80	90	100
	Grains.									
+100	1.977	3.953	5.930	7.906	9.883	11.860	13.836	15.813	17.789	19.766
101	2.034	4.067	6.100	8.134	10.168	12.201	14.234	16.268	18.302	20.335
102	2.092	4.183	6.275	8.367	10.458	12.550	14.642	16.734	18.825	20.917
103	2.151	4.303	6.454	8.606	10.757	12.908	15.060	17.211	19.363	21.514
104	2.212	4.425	6.638	8.850	11.062	13.275	15.488	17.700	19.912	22.125
105	2.275	4.550	6.825	9.100	11.375	13.650	15.925	18.200	20.475	22.750
106	2.339	4.678	7.018	9.357	11.696	14.035	16.374	18.714	21.053	23.392
107	2.405	4.809	7.214	9.619	12.024	14.429	16,834	19.238	21.643	24.048
108	2.472	4.944	7.416	9.888	12.360	14.832	17.304	19.776	22.248	24.720
109	2.541	5.082	7.622	10.163	12.704	15.245	17.786	20.326	22.867	25.408
+110	2.611	5.222	7.834	10.445	13.056	15.667	18.278	20.890	23.501	26.112

NOTE.—The following example of the use of the above table indicates how interpolation for intermediate percentages of saturation may be effected:

What is the weight of vapor in a cubic foot corresponding to a temperature of 70° and a relative humidity of 83 per cent?

At 70° and 80 per cent the weight is .... 6. 384 grs.
The additional weight for 3 per cent is 1/10 the weight for 30 per cent, viz........................ .2394 grs.

Hence the weight at 70° and 83 per cent is.... ... 6. 623 grs.

Relative humidity.—In order to utilize the foregoing table in practical work it is necessary to determine the percentage of humidity in any given case. Generally, it will suffice simply to measure the moisture present in the air adjacent to the place at which operations are being conducted, or at the point at which the air is being drawn into works, kilns, etc. One of the best instruments for this purpose is known as the sling, or whirling, psychrometer, consisting of a pair of thermometers, provided with a handle as shown in Fig. 1, which permits the thermometers to be whirled rapidly, the bulbs being thereby strongly affected by the temperature of and moisture in the air. The bulb of the lower of the two thermometers is covered with thin muslin, which is wet at the time an observation is made.

The wet bulb.—It is important that the muslin covering for the wet bulb be kept in good condition. The evaporation of the water from the muslin always leaves in its meshes a small quantity of solid material, which sooner or later somewhat stiffens the muslin so that it does not readily take up water. This will be the case if the muslin does not readily become wet after being dipped in water. On this account it is desirable to use as pure water as possible, and also to renew the muslin from time to time. New muslin should always be washed to remove sizing, etc., before being used. A small rectangular piece wide enough to go about one and one-third times

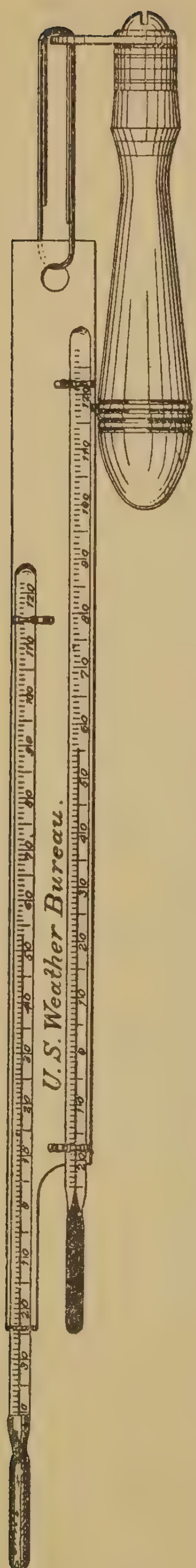

FIG. 1.—Sling psychrometer.

around the bulb, and long enough to cover the bulb and that part of the stem below the metal back, is cut out, *thoroughly wetted* in clean water, and neatly fitted around the thermometer. It is tied first around the bulb at the top, using a moderately strong thread. A loop of thread to form a knot is next placed around the bottom of the bulb, just where it begins to round off. As this knot is drawn tighter and tighter the thread slips off the rounded end of the bulb and neatly stretches the muslin covering with it, at the same time securing the latter at the bottom.

To make an observation.—The so-called wet bulb is thoroughly saturated with water by dipping it into a small cup or wide-mouthed bottle. The thermometers are then whirled rapidly for fifteen or twenty seconds; stopped and quickly read, the *wet bulb* first. This reading is kept in mind, the psychrometer immediately whirled again and a second reading taken. This is repeated three or four times, or more, if necessary, until at least two successive readings of the wet bulb are found to agree very closely, thereby showing that it has reached its lowest temperature. A minute or more is generally required to secure the correct temperature.

When the air temperature is near the freezing point it very often happens that the temperature of the wet bulb will fall several degrees below freezing point, but the water will still remain in the liquid state. No error results from this, provided the minimum temperature is reached. If, however, as frequently happens, the water suddenly freezes, a large amount of heat is liberated, and the temperature of the wet bulb immediately becomes 32°. In such cases it is necessary to continue the whirling until the ice-covered bulb has reached a minimum temperature.

Whirling and stopping the psychrometer.—It is impossible to effectually describe these movements. The arm is held with the forearm about horizontal, and the hand well in front. A peculiar swing starts the thermometers whirling, and afterward the motion is kept up by only a slight but very regular action of the wrist, in harmony with the whirling thermometers. The rate should be a natural one, so as to be easily and regularly maintained. If too fast, or irregular,

the thermometers may be jerked about in a violent and dangerous manner.

The stopping of the psychrometer, even at the very highest rates, can be perfectly accomplished in a single revolution, when one has learned the knack. This is only acquired by practice, and consists of a quick swing of the forearm by which the hand also describes a circular path, and, as it were, follows after the thermometers in a peculiar manner that wholly overcomes their circular motion without the slightest shock or jerk. The thermometers may, without very great danger, be allowed simply to stop themselves; the final motion in such a case will generally be quite jerky, but, unless the instrument is allowed to fall on the arm, or strikes some object, no injury should result.

Exposure.—While the psychrometer will give quite accurate indications, even in the bright sunshine, yet observations so made are not without some error, and, where greater accuracy is desired, the psychrometer should be whirled in the shade of a building or tree, or, as may sometimes be necessary, under an umbrella. In all cases there should be perfectly free circulation of the air, and the observer should face the wind, whirling the psychrometer in front of his body. It is a good plan, while whirling, to step back and forth a few steps to further prevent the presence of the observer's body from giving rise to erroneous observations.

The relation between the readings of the psychrometer and the pressure of the vapor of water mixed with the air is not perfectly understood, although several empirical formulæ have been developed which express this relation more or less exactly. The tables employed by the Weather Bureau were computed by Professor Ferrel's formula, the constants of which were determined from a large number of comparative observations of the psychrometer and Regnault's dew-point apparatus (see W. B. No. 127). The formula is:

$$p = F - 0.000360\ (t - t')\ (1 + 0.00065\, t')\, P$$

p is the desired pressure of the aqueous vapor.

F is the maximum pressure corresponding to saturation at the temperature of the wet bulb.

t equals the air temperature; t' the wet bulb temperature, and P the barometric pressure.

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